EXPERIMENTAL INVESTIGATION OF A RESONANT MECHANISM OF AMPLIFICATION OF CONTINUOUS-SPECTRUM DISTURBANCES IN AN APG BOUNDARY LAYER BY MEANS OF A DETERMINISTIC NOISE METHOD

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1. Introduction

The paper is devoted to an experimental study of the laminar-turbulent transition in a self-similar boundary layer with an adverse pressure gradient (APG). The main attention is paid to dominating mechanisms of weakly-nonlinear interactions between the *wide-band* frequency-wavenumber spectrum of Tollmien – Schlichting (TS) waves (i.e. the noise-like instability waves) and a 2D primary TS-wave. In previous experiments, devoted to weakly-nonlinear stages of the APG boundary-layers transition, only resonant interactions of *deterministic* TS-waves were investigated (see e.g. [1,2]). Moreover, the resonant amplification of the purely controlled (as in the present experiment) wide-band perturbations has not been studied yet even in non-gradient (Blasius) boundary layer, despite there is a great amount of investigations performed for this flow (see [3,4] for review).

2. Basic Flow Structure and Procedure of Measurements

The experiments were performed in the low-turbulence subsonic wind tunnel T-324 of the ITAM at the free-stream velocity U_e = 9.0 m/s measured in a reference point at x = 260 mm. This wind tunnel has a 4 m long test section with a 1 m × 1 m cross-section. The free-stream turbulence level was below 0.02% in the frequency range above 1 Hz. The experimental setup was similar to that used in [5,6]. A sketch of the experiment is shown in Fig. 1. The boundary layer under investigation developed on a flat plate, which had a chord length of 1.49 m, a span of 0.99 m, and a thickness of 12 mm. The APG was induced over the plate by an adaptive wall-bump mounted on the test-section ceiling. The bump and the flap were adjusted in a way to have over the plate a streamwise APG, which would correspond to a fixed Hartree parameter β_H = −0.115. As shown in [5,6], the basic flow structure both outside and inside the boundary layer is in a very good agreement with the theoretical one calculated by B.V. Smorodsky for this value of β_H. A set of wall-normal mean-velocity profiles measured at various streamwise positions is shown in Fig. 2. It is seen that the experimental profiles agree very well with the profile calculated for β_H = –0.115, which has an inflexion point at U/U_e = 0.42 (y/δ_1 = 0.8).

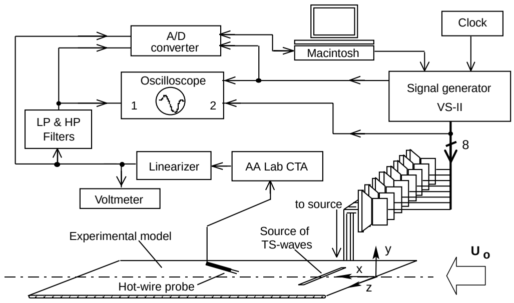


Fig. 1. Sketch of experimental setup

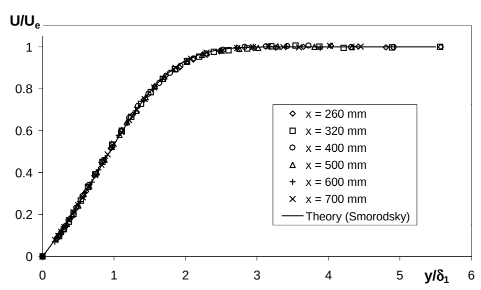


Fig. 2. Experimental and theoretical mean velocity profiles.

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
23 Aug 2002	N/A	-

Title and Subtitle Experimental Investigation of a Resonant Mechanism of Amplification of Continuous-Spectrum Disturbances in an APG Boundary Layer by Means of a Deterministic Noise Method	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Institute of Theoretical and Applied Mechanics Institutskaya 4/1 Novosibirsk 530090 Russia	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) EOARD PSC 802 Box 14 FPO 09499-0014	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes See also ADM001433, Conference held International Conference on Methods of Aerophysical Research (11th) Held in Novosibirsk, Russia on 1-7 Jul 2002	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 6	

The experiments were conducted at controlled disturbance conditions. Three different regimes of excitation were studied: regime NR (Noise with Resonance) regime F (Fundamental wave only), and regime N (Noise only). The same 2D fundamental wave was excited in regimes NR and F but it was not excited in regime N. This wave was harmonic in time and had frequency f_1 = 109.1 Hz. At the position of the disturbance source (U_e = 8.80 m/s) this frequency corresponds to the frequency parameter $F = 2\pi f\nu/U_e^2\cdot 10^6 = 135.8$. Similarly, the same quasi-random, noise-like TS-waves were excited in regimes NR and N but they were absent in regime F. In addition, three previously studied 'deterministic' regimes were used for comparison. They are: regime MR [8] (Main Resonance), regime MRDS [2] (Main Resonance with Small frequency Detuning), and regime S [8] (Subharmonic only). In regime MR three waves were excited simultaneously: (i) the fundamental 2D wave (f_1 = 109.1 Hz, $\beta = 0$) and (ii) a pair of oblique subharmonic waves ($f_{1/2}$ = 54.6 Hz, $\beta = \pm\beta_{1/2} = \pm 0.131$ rad/mm) with relatively small initial amplitudes. In regime MRDS a pair of oblique quasi-subharmonic modes with frequency $f = 0.9f_{1/2}$ was excited instead of the subharmonic pair. In regime S only a pair of oblique subharmonic modes was excited.

All instability waves were excited by one (universal) disturbance source described in more detail in [7] by means of weak blowing/suction air fluctuations through a slit in the flat-plate surface, which was perpendicular to the flow direction. The slit had a width of 0.8 mm and length of 164 mm. A block of 82 copper tubes (of 2 mm in diameter) was located on the bottom of the slit. The source was able to excite both 2D and 3D TS-waves with almost any desirable spanwise-wavenumber spectrum. Each tube was connected with a flexible plastic pipe to one of eight loudspeakers. The source was mounted flush with the wall at a distance x_s = 300 mm. In this position the local Reynolds number Re $U_e\delta_1/\nu = 770$, where $\nu = 1.535\cdot 10^{-5}$ m^2/s is the air kinematic viscosity. The electric signals, which fed the loudspeakers, were generated by an electronic unit VS-II, which had eight channels and was controlled by a computer. The signals were formed by a computer program for each (of eight) channel separately, then downloaded into RAM of unit VS-II, and played back with a rate controlled by an external clock. A special signal, which had the frequency of repetition of the recorded realization, was used as a reference one for the data acquisition system, in particular for the ensemble averaging of the hot-wire signals, which were linearized and introduced into an Apple computer via an A/D converter.

The noise-like disturbances had a wide, continuous frequency-wavenumber spectrum and were pseudo-random both in time and in space (in the spanwise direction). However, this component of the signal repeated every 20 fundamental periods (i.e. approximately every 0.5 s). During this time the excited TS-waves had been traveled far downstream for a distance that was greater than the total plate length. Therefore, from the viewpoint of the flow the generated continuous-spectrum perturbations can be regarded as random (i.e. non-deterministic) ones. Meanwhile, from the viewpoint of the data analysis these perturbations are periodic (i.e. deterministic) ones. These signals could be ensemble averaged and their phases could be easily determined by means of usual Fourier-series spectral decomposition. Each of 8 channels of unit VS-II produced an *individual* noise-like signal. All eight signals had approximately the same amplitude frequency spectrum but different phases of the spectral modes. The experimental approach based on such signals we call the *deterministic noise method*.

Two typical time-traces of the VS-II output signals produced in regime NR at channels 1 and 2 are shown in Fig. 3*a* as an example. It is seen that the disturbances superimposed to the sinusoidal signal look really like random ones and they are different for different channels. The averaged (for all eight channels) amplitude frequency spectrum of the noise signal is presented in Fig. 3*b*. The peak in this spectrum corresponds to the fundamental mode, while the continuous spectrum (like the so-called 'white noise') corresponds to the random disturbances.

3. Experimental Results

At a fixed initial spectrum of the noise-like disturbances, the character of the downstream evolution of the instability-wave spectra was found to be dependent essentially on the presence

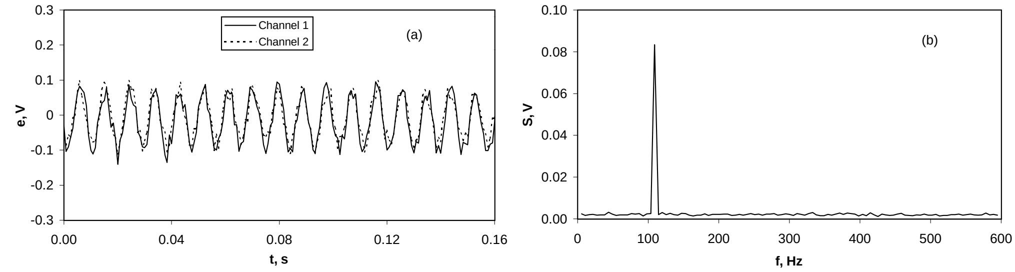


Fig. 3 . Typical time-traces of VS-II output signals (*a*) and their frequency spectrum (*b*) produced in regime NR.

of the fundamental TS-wave. This very strong distinction between regimes N and NR is very well seen from comparison of the spectra presented in Figs. 4*a* and 4*b* respectively. The spectra were measured at distances from the wall corresponded to the subharmonic maximum. In absence of the fundamental instability wave (Fig. 4*a*, regime N) the disturbances are amplified only in the frequency range, which corresponds to unstable linear TS-waves inside the neutral curve. The theoretical positions of the lower and upper branches of this curve are indicated in Fig. 4 for 2D TS-waves. When the fundamental instability wave is switched on (Fig. 4*b*, regime NR) the character of the frequency spectra changes radically. Now the amplification is observed in a very wide frequency range, which extends far outside the neutral stability curve. The largest spectral amplitudes are now observed in the vicinity of the subharmonic frequency. The values of the spectral amplitudes are much larger in regime NR compared to regime N.

The amplification curves measured for several spectral modes selected from the wide-band noise in regime N have shown their very good agreement with those obtained in the linear stability experiments [5, 6] in a range of the TS-wave spanwise wavenumbers β from 0 to 0.134 rad/mm. A very well agreement has also been observed for the downstream phase distributions for these modes. The wall-normal profiles measured at x = 510 mm for spectral components (selected for several frequencies from the continuous spectrum of the noise-like perturbations amplified in regime N) have shown that their shapes are rather typical for the 3D TS-waves observed in [6]. Thus, all main properties of the continuous-spectrum modes developing in regime N were found to correspond to those of the 3D (in general) linear TS-waves.

The wall-normal disturbance profiles measured at the subharmonic frequency ($f = f_{1/2}$ = 54.5 Hz) in regimes NR and MR are presented in Fig. 5. Both the amplitude and phase profiles are seen to be very close to each other in these regimes. Together with the agreement of the profile shapes observed in regimes MR and S (see [8]) this fact indicates to a closeness of the amplified perturbations to the linear 3D TS-modes. In particular, this means that the subharmonics amplified in regime NR from the noise have approximately the same range of the spanwise wavenumbers as those amplified in regimes MR and S. This conclusion is supported

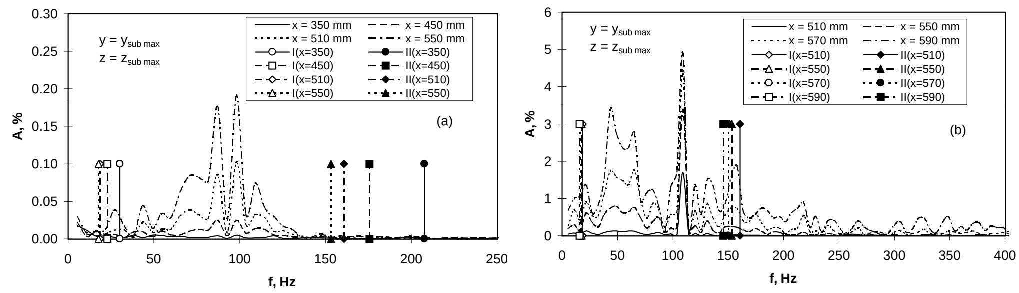


Fig. 4. Downstream evolution of disturbance spectra in regimes N (*a*) and NR (*b*).

by the spanwise distributions presented in Fig. 6 and measured in regime NR at several streamwise positions for a frequency harmonic close to the subharmonic one. It is seen that the amplified disturbance correspond to two oblique modes with the spanwise wavenumbers $\beta = \pm 0.131$ rad/mm, superposition of which gives rise the observed standing-wave picture with the spanwise period $\lambda_z = 48$ mm. Exactly the same picture was found previously in regime MR [8].

The amplification curves obtained in regime NR for the fundamental wave and for several spectral components selected from noise are shown in Fig. 7*a* in comparison with those measured in regime MR [8] for the fundamental and subharmonic waves. The measurements are performed at $z = 16$ mm at the wall-normal distances, which correspond to the subharmonic amplitude maximum. It is seen that the downstream behavior of the low-frequency modes in regime NR is rather similar to that found for the subharmonic mode in 'deterministic' regime MR. In particular, the amplitudes of the noise components grow in regime NR double-exponentially similarly to the subharmonics in regime MR. A very good agreement is also found for amplification curves measured in regimes NR and MRDS (not shown) for harmonics around frequencies $f_{1/2}$ and $f_{3/2}$. The comparison of two curves (from those presented in Fig. 7*a*) measured in regime NR with the corresponding curves obtained in regime N (noise only) is presented in Fig. 7*b*. This figure shows that the rapid double-exponential growth of the noise occurs exclusively due to its interaction with the fundamental TS-wave.

The frequency range of amplification of the noise-like perturbations in regime NR is seen very well in Fig. 8 in comparison with corresponding range observed in the non-resonant regime N. The amplification factors $\kappa(f) = A(f,x{=}550)/A(f,x{=}350)$ shown in this figure characterize an integral growth of the frequency harmonics in regime NR observed within the spatial interval between the "initial" position ($x = 350$ mm) and one of last stages of the resonant amplification ($x = 550$ mm). The values of κ shown in Fig. 8 are smoothed in the frequency domain by means of the sleeping average method within the frequency interval ±24 Hz. During calculation of these amplification factors in regime NR the fundamental wave and its higher harmonics were excluded from the spectra. In absence of the fundamental instability wave (regime N) the

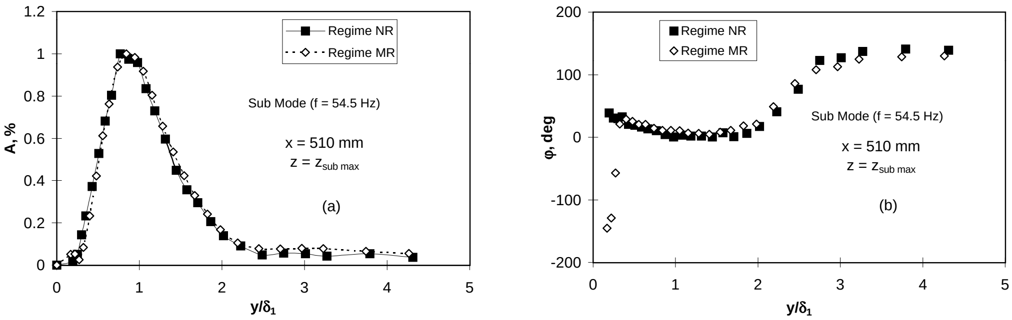


Fig. 5. Comparison of profiles of subharmonic amplitude (*a*) and phase (*b*) measured in regimes NR and MR [8].

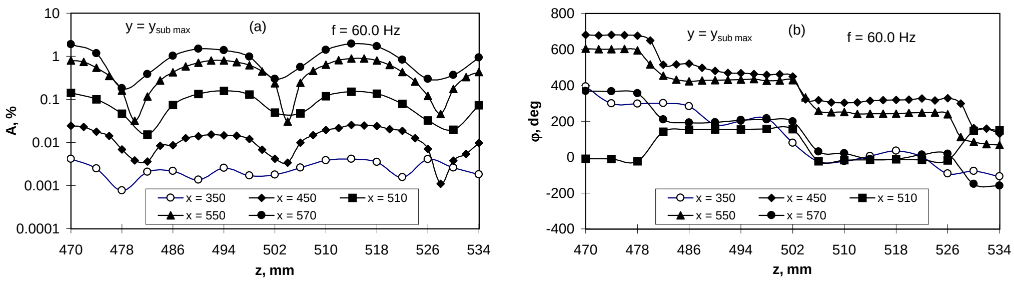


Fig. 6. Downstream evolution of spanwise distributions of subharmonic amplitude (*a*) and phase (*b*) in regime NR.

amplification (a rather weak one) is observed only in the frequency range that corresponds to the neutral stability curve, the upper and lower branches of which are indicated in Fig. 8 for $x = 350$ and 550 mm for 2D TS-waves. When the fundamental wave is switched on (regime NR) the noise-like perturbations grow very intensively in the whole studied frequency range. The largest amplification factors are observed in rather wide sub-ranges in the vicinity of the subharmonic wave ($f_{1/2} = 54.5$ Hz) and its higher even harmonics ($f = (2n+1)f_{1/2}$, $n = 1, 2, 3$). Note that even in the vicinity of the fundamental wave and its higher harmonics ($f = nf_1$, $n = 2, 3, 4$) an additional (resonant) amplification of the continuous-spectrum modes takes place in regime NR.

The information about the disturbance phase synchronism can be obtained from analysis of their phase velocities. The results are presented in Fig. 9. The phase velocities $C_x(f) = 2\pi f/\alpha_r(f)$ are obtained with the help of the streamwise wavenumbers determined as $\alpha_r(f) = \Delta\varphi(f)/\Delta x$ ($\Delta x = 550 - 470 = 80$ mm), i.e. as the averaged values of the tangent of the phase-growth inclination angle within the range $x = 470 \div 550$ mm. Coincidence of phase velocities for any two spectral modes indicates that the synchronism condition is satisfied for them (see e.g. [9]).

The dispersion curve $C_x = C_x(f)$ obtained in regime N (noise only) is shown in Fig. 9*a*. The phase velocity of the noise frequency components increases (in average) with frequency and tends to zero when $f \rightarrow 0$. The comparison with the phase velocities of deterministic instability modes obtained in [6] is also presented in Fig. 9*a* for spanwise wavenumbers $\beta = 0$ and 0.134 rad/mm. A good agreement is observed. This comparison shows also that in regime N either 2D or 3D waves dominate in the flow depending on frequency. The dispersion (i.e. the dependence of C_x on f) is very significant in regime N, especially for low frequencies.

When the fundamental instability wave is switched on (regime NR) the dispersion characteristics of the noise-like perturbations change radically (Fig. 9*b*). In fact, the dispersion disappears, i.e. the phase velocities for all frequencies become practically the same. The comparison with the phase velocities of deterministic modes, observed in resonant regimes MR

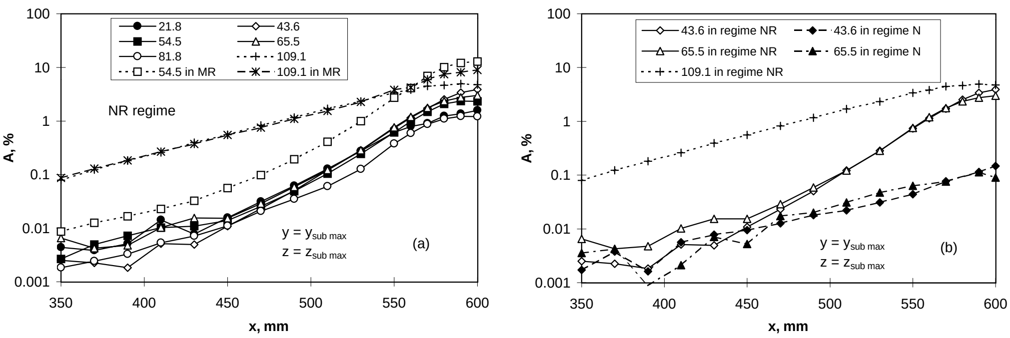


Fig. 7. Amplification curves for several spectral modes in regime NR in comparison with regimes MR (*a*) and N (*b*).

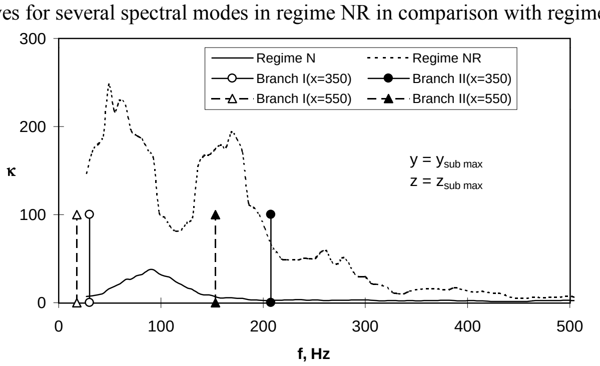
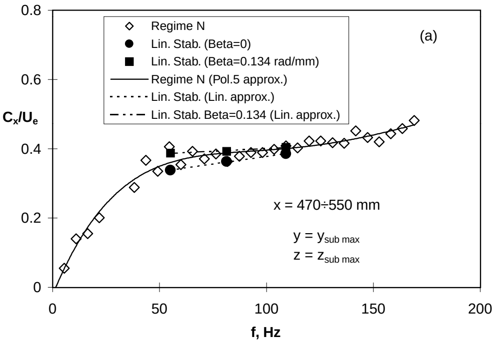


Fig. 8. Amplification factors of continuous-spectrum components in regimes NR and N versus frequency.



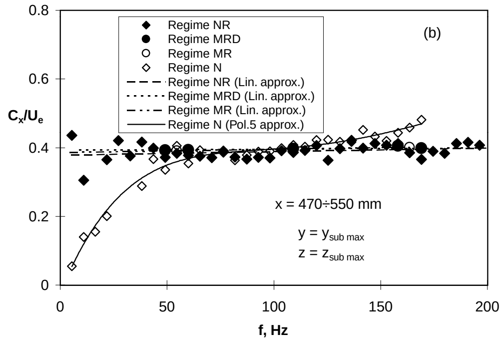


Fig. 9. Dispersion curves measured in regimes N and NR in comparison with regimes MR and MRD.

and MRDS, shows (Fig. 9*b*) that the phase synchronism condition for the subharmonic resonance — $C_x(f) = C_x(f_1)$ — is satisfied in regime NR (similar to the deterministic resonant regimes) in a wide range of frequencies. The mechanism of the phase synchronization of the resonantly amplified modes described in [2] leads in regime NR to a tuning up the phases of these modes with respect to the fundamental wave phase.

4. Conclusions

The present study has shown that the random (continuous-spectrum) low-amplitude instability waves are amplified double-exponentially in the APG-boundary-layer transition due to their resonant interaction with the 2D primary TS-wave. This resonant mechanism has the same physical nature as the subharmonic resonance but is able to amplify "background" disturbances in a very wide frequency range with the largest growth rates in the vicinity of the subharmonic mode and its highest add harmonics. These results, together with those obtained in [2, 8], indicate that the subharmonic-type resonant interaction of TS-waves represents the main mechanism of initial stages of the nonlinear disturbance development in the APG boundary layer.

This work is supported by Russian Foundation for Basic Research (grant No. 00-01-00835).

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